Load Control Using Building Thermal Mass

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This paper provides an overview of research related to use of building thermal mass for shifting and reducing peak cooling loads in commercial buildings. The paper presents background on the concept and the problem of optimizing zone temperature setpoints and provides specific results that have been obtained through simulations, controlled laboratory testing, and field studies. The studies have demonstrated significant savings potential for use of building thermal mass in commercial buildings. However, the savings are sensitive to many factors, including utility rates, type of equipment, occupancy schedule, building construction, climate conditions, and control strategy. The paper also attempts to provide an assessment of the state of the art in load control using building thermal mass and to identify the steps necessary to achieve widespread application of appropriate control strategies. [DOI: 10.1115/1.1592184]

Building Thermal Mass Concept

In conventional control strategies, the thermal storage of a building is not utilized for reducing operating costs. When the building is not occupied, the thermostat is set up to a higher temperature for cooling or set back to a lower temperature for heating such that the equipment is generally off during these periods. Optimal start algorithms determine the times for turning equipment on so that the building zones reach the desired conditions at a time when the building becomes occupied. The goal of these algorithms is to minimize the precool (or preheat) time. During occupied hours, the zone conditions are typically maintained at constant setpoints. For these conventional night setup/setback strategies, the assumption is that building mass works to increase operating costs. A massless building would require no time for precooling (or preheating) and would have lower overall cooling (or heating) loads than actual buildings. However, under proper circumstances, use of a building's thermal storage for load shifting can significantly reduce operational costs, even though the total zone loads may increase.

At any given time, the cooling requirement for a space is due to convection from internal gains (lights, equipment, and people) and interior surfaces. Since a significant fraction of the internal gains is radiated to interior surfaces, the state of a building's thermal storage and the convective coupling dictates the cooling requirement. Precooling of the building during unoccupied times reduces the overall convection from exposed surfaces during the occupied period as compared with night setup control and can reduce daytime cooling requirements. The potential for storing thermal energy within the structure and furnishings of conventional commercial buildings is significant when compared to the load requirements. Typically, internal gains are on the order of 3–7 W per square foot of floor space. The thermal capacity for typical concrete building structures is on the order of 2–4 Wh/°F per square foot of floor area (12–24 Wh/°C-m^2). Thus, for an internal space, the energy storage is on the order of 1 hr for every °F (0.5°C) of precooling of the thermal mass.

Opportunities for reducing operating costs through use of building thermal mass for cooling are due to four effects: reduction in demand costs, use of low cost off-peak electrical energy, reduced mechanical cooling resulting from the use of cool nighttime air for ventilation precooling, and improved mechanical cooling efficiency due to increased operation at more favorable part-load and ambient conditions. However, these benefits must be balanced with the increase in total cooling requirement that occurs with precooling of the thermal mass. Therefore, the savings associated with load shifting and demand reductions depend upon both the method of control and the specific application.

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Optimizing Zone Temperature Setpoints

Optimal zone temperature setpoints are a complicated function of several factors, including the utility rates, load profile, equipment characteristics, building storage characteristics, and weather. For a utility rate structure that includes both time-of-use energy and demand charges, the optimal strategy can actually depend upon variables that extend over a monthly time scale. The overall problem of minimizing utility costs over a billing period (e.g., a month) can be mathematically described as follows:
Minimize:

$$J=\sum_{k=1}^{N}\{EC_kP_k\Delta t\}+Max_{1\le k\le N}\{DC_kP_k\} \tag{1}$$

with respect to the trajectory of zone temperature setpoints $(T_{z,1},T_{z,2},\ldots\ldots T_{z,N})$ and subject to the following constraints for each stage k:

$$T_{z,\min,k}\le T_{z,k}\le T_{z,\max,k} \tag{2}$$

$$\vec{x}_k=f(\vec{x}_{k-1},T_{z,k},k) \tag{3}$$

$$\vec{x}\le\vec{x}_k\le\vec{x}_{\max} \tag{4}$$

$$\vec{x}_N=\vec{x}_0 \tag{5}$$

where J is the utility cost associated with the billing period (e.g., a month), Δt is the stage time interval (typically equal to the time window over which demand charges are levied, e.g., 0.25 hr), N is the number of time stages in a billing period, and for each stage k: P is the average building electrical power (kW), EC is the energy cost rate or cost per unit of electrical energy ($/kWh), DC is the demand charge rate or cost per peak power rate over the billing period ($/kW), $T_{z,k}$ is the zone temperature setpoint which regulates both the comfort conditions and the rate of energy removal from or addition to the building structure over the stage, $T_{z,\max}$ is the maximum value for T_z, $T_{z,\min}$ is the minimum value for T_z, $\vec{x}_k$ is a vector of states that define the condition of the energy storage within the building structure at the end of the stage, $\vec{x}_{k,\max}$ is the maximum admissible states of storage, $\vec{x}_{k,\min}$ is the minimum admissible states of storage, and f is a state Equation that relates the state of storage at stage k to the previous state and current control.

The first and second terms in Eq. (1) are the total cost of energy use and building demand for the billing period. Both the energy and demand cost rates can vary with time, but typically have at least two values associated with on-peak and off-peak periods. An even more complicated cost optimization would result if the utility included ratchet clauses whereby the demand charge is the maximum of the monthly peak demand cost and some fraction of the previous monthly peak demand cost within the cooling season. For the special case of real-time utility rates, the demand charge may be not present and the energy charges can vary hourly in response to the actual costs of producing electricity.

The equality constraint of Eq. (3) is the state equation that results from a model of energy flows in the building. The state of storage at any stage k is a function of the previous state (x_{k-1}), the zone control ($T_{z,k}$), and other time-dependent factors (e.g., ambient temperature, solar radiation). In a building, the energy storage is highly distributed in walls, floor, furnishings, etc. As a result, many individual states are required to characterize the dynamics. The constraints of Eqs. (2) and (4) are associated with comfort and equipment capacity considerations. The constraint of Eq. (5) forces a steady-periodic solution to the problem. This constraint becomes less important as the length of analysis increases.

The total building power in Eq. (1) can be replaced with the power associated with the air conditioning equipment if the non-cooling electrical power is relatively constant during the occupied, on-peak period. In order to determine a control strategy for charging and discharging storage that minimizes this cost function for a given system, it would be necessary to perform a minimization over the entire billing period because of the influence of the demand charge. In this case, the number of optimization variables is equal to the number of time steps within the month. The problem can be simplified by decoupling the optimization associated with the energy and demand charges. The optimization problem is posed as a series of shorter-term (e.g., daily) optimizations with a constraint on the peak demand charge according to:
Minimize:

$$J=\sum_{k=1}^{N}\{EC_kP_k\Delta t\}+TDC \tag{6}$$

with respect to the control variables ($T_{z,1},T_{z,2},\ldots..T_{z,N}$) and a billing period demand cost target (TDC) and subject to the constraints of Eqs. (2)–(5) and the following equation:

$$DC_kP_k\leq TDC \tag{7}$$

The constraint expressed in Eq. (7) arises from the form of the cost function chosen for Eq. (6). At each stage, the demand cost must be less than or equal to the peak demand cost for the billing period. The peak or target demand cost, TDC, is an optimization variable that affects both energy and demand costs. The advantage of posing the optimization problem using Eq. (6) rather than Eq. (1) is that it simplifies the numerical solution. For a given value of TDC, the problem could be solved as a series of daily optimizations ($N=24\Delta t$). An optimal value of TDC could then be determined using a one-dimensional search applied to a monthly cost function.

The problem of determining optimal trajectories of zone temperature setpoints for buildings is important because it establishes a benchmark for the maximum cost savings associated with simpler near-optimal control approaches. Braun [1], Synder and Newell [2], Keeney and Braun [3], Chen [4], and Nagai [5] have considered various aspects of this optimization problem. For example, Braun [1] applied nonlinear optimization techniques on a daily basis to determine results for two limiting cases: 1) minimum daily energy costs with time-of-use electric rates and 2) minimum peak demand. This is a much simpler problem than determining minimum operating costs based upon both energy and demand costs, but it does provide useful information with respect to the savings potential. More recently, Nagai [5] presented a method for minimizing energy and demand costs on an annual basis that relies on a second-order transfer function model for the cooling requirements. The use of a low-order model allows practical application of dynamic programming for determining the optimal control trajectories.

Simulated Savings

Several simulation studies have demonstrated a substantial benefit in precooling buildings. Braun [1] applied optimization routines to computer simulations of buildings and their associated cooling systems in order to estimate cost savings associated with optimal control of building thermal mass. Maximum energy cost and demand savings for optimal control of building thermal mass

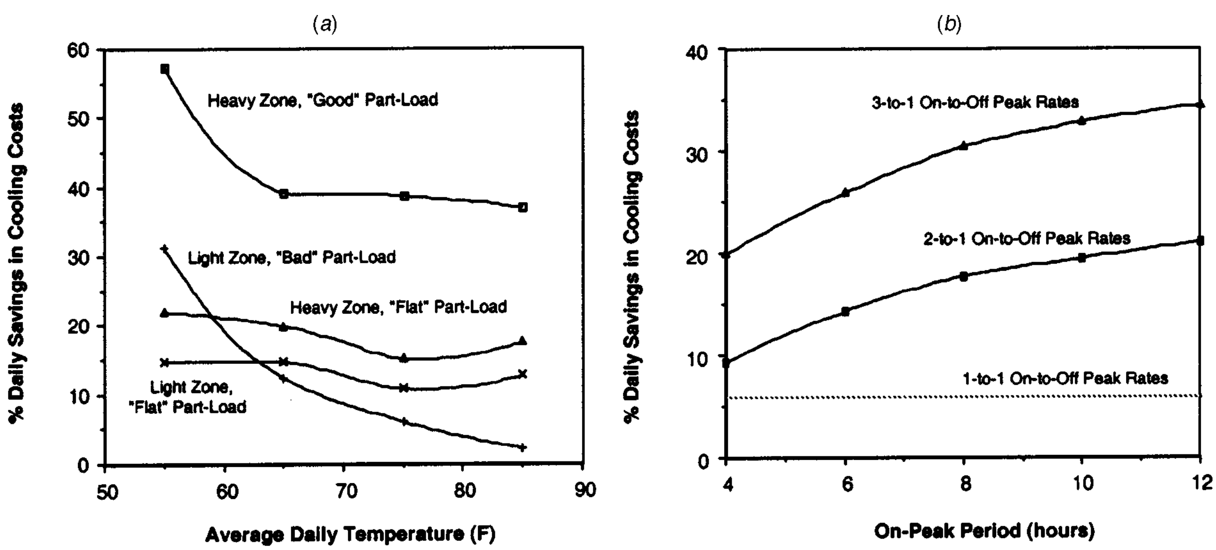


Fig. 1 Daily energy cost savings for optimal versus night setup control: *a*) 12-hr on-peak period, 2-to-1 on-peak to off-peak electrical rates; *b*) heavy zone, flat part-load performance, 80°F mean ambient temperature (on-peak period centered at noon, clearness index=0.6, from Braun [1])

were compared with conventional night setup control for typical days. For a design day, maximum energy cost savings for cooling associated with optimal control of building thermal mass ranged from 0 to 35%, depending upon the system and utility rates. For the minimum demand problem, it was possible to reduce the total building peak electrical demand by between 15–35% on the design day.

Synder and Newell [2] also determined optimal control for a single day using a simple building and cooling system model and used these results to estimate monthly costs. Cooling cost savings for a representative building and utility rate structure were estimated to be 18% as compared with conventional control.

Rabl and Norford [6] used a simple building model to study the impact of building precooling on peak cooling loads. The building was precooled at a constant temperature and the building temperatures were adjusted during the occupied period to provide the lowest peak load. For the building considered in their study, the peak load was reduced by between 10–20%, depending upon the duration of the pre-cool period.

Andresen and Brandemuehl [7] also demonstrated the potential savings in peak cooling rate associated with precooling strategies. They investigated the impact of three different pre-cool strategies for a single building and found as much as a 50% reduction in peak cooling rate when compared to conventional night setup control. The results were sensitive to the convective coupling between the air and the thermal mass and the mass of the furnishings was found to be important.

There are two very important conclusions that can be made regarding the potential for use of building thermal mass that resulted from the simulation studies: 1) there is a tremendous opportunity for reductions in on-peak energy and peak demand and 2) the savings potential is very sensitive to the utility rates, building and plant characteristics, weather conditions, and occupancy schedule. In order to demonstrate these points, some sample results from Braun [1] are presented.

Figure 1 gives percent daily energy cost savings for optimal control as compared with conventional night setup control for different buildings, cooling plants, mean daily ambient temperatures, and utility rates. The daily variations in solar radiation, ambient temperature, and ambient humidity were simulated using statistical correlations that utilize mean daily values as inputs. A single story in a multi-zone building was modeled assuming two types of construction that span a range typical of high-rise buildings with carpeted floors. A chilled water cooling plant was considered with a variable-air-volume air handling unit and assuming three different part-load characteristics: good, flat, and poor. The *good* part-load plant utilizes variable-speed motors for all equipment including the chillers, pumps, and fans and the best performance occurs at about 30% of the design load. The performance of the *flat* part-load plant is independent of load and would be representative of a plant with several stages of chillers, pumps, and towers that are in parallel and sequenced according to the load. The *poor* part-load plant utilizes all fixed-speed equipment with only a single stage of operation for each device and the best efficiency occurs at full load. The building was occupied from 6 a.m.–6 p.m., had an on-peak period from 8 a.m.–8 p.m., and had a 2-to-1 ratio of on-peak to off-peak electrical rates. Demand charges were not considered in this analysis. During the occupied period, the zone temperature was constrained to be between 68–76°F.

Figure 1*a* shows that as a percentage of daily costs, the savings are greatest at low ambient temperatures where the greatest *free* cooling opportunities exist. The system with the *good* part-load performance has opportunities for significant savings over the entire range of weather conditions for both light and heavy building construction. The opportunities are much less significant for systems with less favorable plant part-load characteristics. At high temperatures, the savings approach zero for the *bad* part-load characteristics. In the absence of *free* cooling at high temperatures, the penalty associated with operating at part-load offsets the utility incentives associated with shifting loads from the on-peak to the off-peak period. Even at low ambient temperatures, the *free* cooling opportunities are smaller for flat and poor part-load systems than for the *good* part-load plant because of the use of variable-pitch rather than variable-speed air-handler fans. Figure 1*a* also shows that the plant performance characteristics are more important than the construction materials. Typical commercial buildings have sufficient thermal mass to provide significant load shifting.

Figure 1*b* shows the effect of the number of hours for on-peak electric rates (centered about noon) and the ratio of on-peak to off-peak rates. In general, better opportunities exist for higher ratios of on-peak to off-peak rates and longer on-peak hours. However, the savings are more sensitive to the ratio of on-peak to off-peak rates than to the length of the on-peak period. It is interesting to note that the savings approach a maximum with increasing on-peak period. In the limit, the percent savings for a zero-length on-peak period equal those for a 24-hr period.

Figure 2 shows hourly variations in zone temperatures and cooling energy for both optimal and night setback control for a

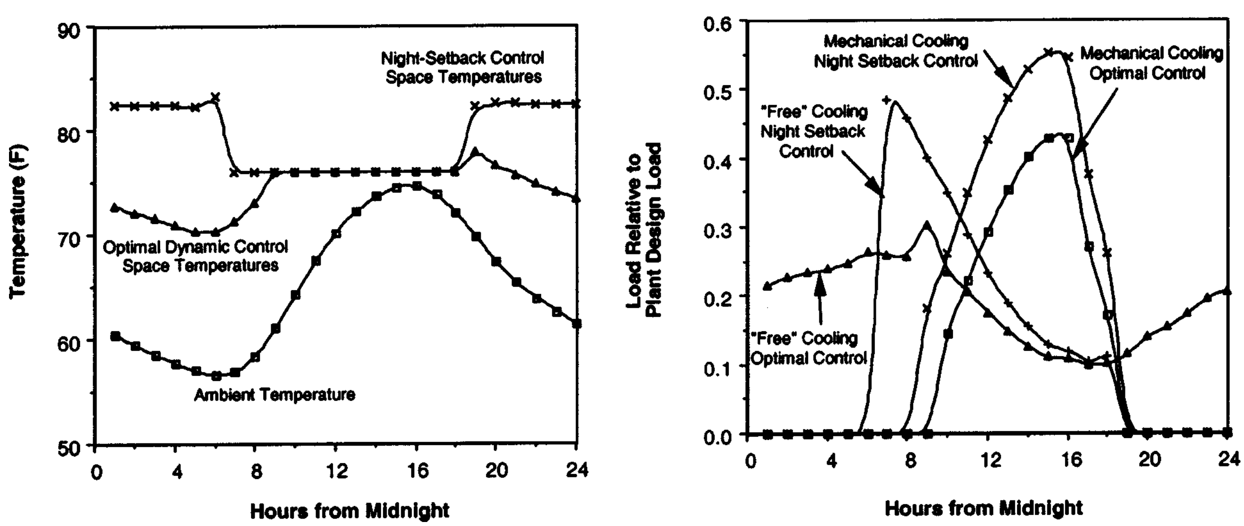


Fig. 2 Example daily variations in space temperatures *a*) and cooling quantities *b*) for optimal and night setup control (no time-of-day rates, heavy zone with *good* part-load plant, clearness index=0.6, average ambient temperature=65°F, from Braun [1])

day with significant opportunities for nighttime free cooling. The optimal strategy was determined with no time-of-use rates and no demand charge considerations. The building was precooled using ambient ventilation beginning shortly after the end of the occupied period to a minimum temperature of 70°F. As internal gains increased due to occupancy, the space temperatures was increased to an upper limit of 76°F. The zone space temperature remained at the upper comfort limit for a large portion of the occupied period. This tends to minimize gains from the interior surfaces during this time. In contrast, the conventional strategy maintained 76°F throughout the occupied period, while the space temperature floated freely during unoccupied times. The amount of (and peak) mechanical cooling required for the system was significantly less with optimal control as compared with the conventional strategy. This reduction was due to *free* precooling during the nighttime hours. The time variation in the *free* cooling energy approximately mirrored the variation in ambient temperature (greater at lower ambients). *Free* cooling for the conventional strategy peaked when the system turned on to bring the space temperature to the occupancy setpoint. The system operated without mechanical cooling until *free* cooling alone could no longer maintain the setpoint.

Figure 3 shows the potential for reducing the peak daily electrical use for a building with an optimal strategy as compared with conventional night setback control. These results were developed by optimizing the trajectory of zone setpoints in order to minimize the peak electricity. For all systems considered, the reduction in peak electrical use associated with optimal control is very significant. Again, the greatest potential savings exist for heavy zones and with cooling plants having *good* part-load characteristics. For the most part, the reductions in peak demand increase with increasing ambient temperature as the electrical energy associated with cooling requirements becomes a larger portion of the total building electrical use. The only exception occurred at low ambient temperatures with a poor part-load plant.

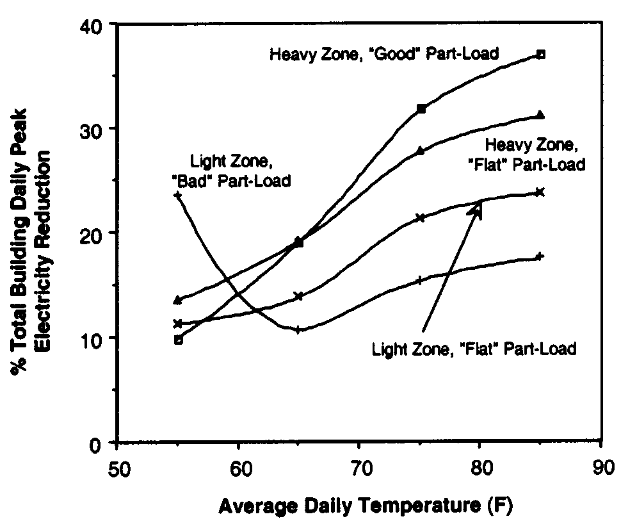
Figure 3*b* shows that both the peak daily electrical use and the energy costs associated with optimal control for minimum peak consumption are sensitive to the minimum unoccupied temperature. The maximum peak reduction associated with optimal control increases with decreasing minimum unoccupied temperature, but at the expense of significantly increased energy costs. Part of the reason for the energy cost penalty is associated with requirements for heating at the time of occupancy. Below a minimum temperature of about 58°F, the energy costs are greater than those for conventional control (i.e., negative savings). The maximum energy cost savings and associated peak reduction are not affected by the minimum unoccupied zone temperature for this system, because the optimal control does not bring the precooled space temperature below 65°F. It is interesting to note that the peak reduction associated with the minimum cost strategy is not significantly less than the maximum possible at a minimum temperature of about 65°F. This was also found to be the case for other systems considered.

The potential for use of building thermal mass also depends on the occupancy schedule. There is little benefit in precooling for a building that has 24-hr occupancy (e.g., a hospital) or a building that is occupied at night and unoccupied during the day.

Laboratory Studies

The advantage of performing laboratory tests as compared with field measurements is that different control strategies can be compared for the same set of operating conditions. Conniff [8] performed experiments using a test facility at the National Institute of Standards and Technology (NIST) in order to investigate the potential for peak load reduction through use of building thermal mass. This structure was designed to represent a thermal zone within a multi-story building. External boundary conditions for the floor, ceiling, and walls could be controlled independently. The structure was of relatively lightweight construction, having a 2-in. concrete floor, suspended ceiling, and gypsum walls. The floor was carpeted and there were no special provisions for coupling to the thermal mass. The purpose of their study was to investigate the effect of alternative control procedures on the peak air conditioning load. The strategies that they investigated resulted in less than a 3% reduction in the peak cooling load. However, the strategies were adhoc and were not optimized for the facility.

Morris et al. [9] also used the NIST facility as an internal zone and performed a set of experiments in order to demonstrate the potential for load shifting and load leveling when the control was optimized. Prior to performing experiments, a simulation of the test facility was developed that included a model of the structure, a model for human comfort, a specific profile of internal gains, and a model of a hypothetical cooling system that would serve the structure. Results of the zone simulation were compared with measurements and good agreement was achieved. In order to determine the control strategy to use in the experiments, optimization routines were applied to the simulation with the constraint that thermal comfort must be maintained during the occupied period. Two separate objectives resulting in two different control



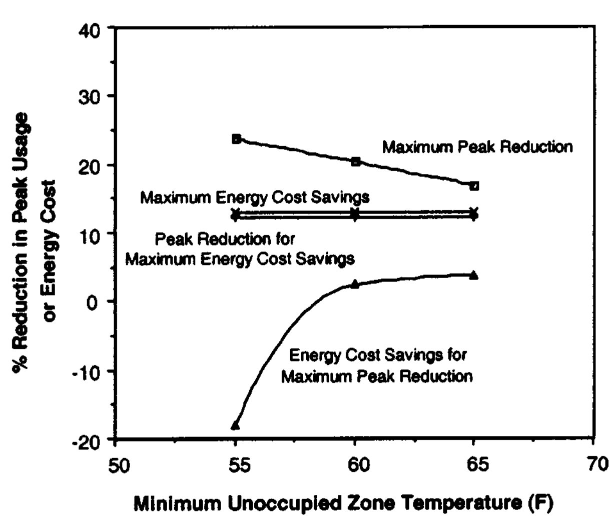


Fig. 3 Daily peak electrical usage reduction for optimal versus night setback control: *a*) minimum unoccupied setpoint =55°F; *b*) average ambient temperature=85°F (on-peak period: 8 a.m.–8 p.m., 2-to-1 on-to-off peak rates, light zone with *flat* part-load, clearness index=0.6, from Braun [1])

strategies were considered: 1) minimum cooling system energy use and 2) minimum peak cooling system electrical demand. The two strategies were implemented in the facility and compared with night setup control. The results of these tests were dramatically different than those obtained by Conniff for the same facility. A brief summary of these results follows.

Figure 4 shows the 24-hr time variation in cooling requirement and comfort conditions for the test facility allowed to reach a steady-periodic condition for both the minimum energy use strategy and conventional night setup control. The results indicate a significant load shifting potential for the optimal control. Overall, the cooling requirements during the occupied period were approximately 40% less for optimal than for night setup control (labeled night setback in Fig. 4). The time variation of Predicted Mean Vote (PMV) is also shown for the two control strategies as determined from measurements at the facility. A PMV of zero is a thermally neutral sensation, while positive is too warm and negative too cool. In the region between plus and minus 0.5, comfort is not compromised to any significant extent. Figure 4 shows that the comfort conditions were essentially identical for the two control methods during the occupied period. The indoor air temperature, which has a dominant effect upon comfort, was maintained at 75°F during the occupied period for both control methods. During the unoccupied period, the cooling system was off for night setup control and the temperature floated to *warm* comfort conditions. On the other hand, the optimal controller precooled the space, resulting in *cool* comfort conditions prior to occupancy. During these tests, the minimum space temperature during precooling was 68°F, while the space temperature setpoint was raised to 75°F just prior to occupancy.

Figure 5 shows the 24-hr time variation in cooling requirement and comfort conditions for the test facility for both the minimum peak demand strategy and conventional night setup control. The optimal control involved precooling the structure and adjusting the space temperatures within the comfort zone ($-0.5<$PMV <0.5) during the occupied period to achieve the minimum demand. Although the minimum possible demand was not achieved during the tests, the peak cooling rate during the occupied period was approximately 40% less for minimum peak demand control than for night setup control. The precooling period only lasted until about 3 a.m., followed by a natural warmup period of about 3 hr prior to occupancy. The entire range of the comfort region was utilized during the occupied period.

An important conclusion from these results is that it is important to develop control strategies that are specific to the applications. The results of Coniff [8] were not nearly as encouraging as those of Morris et al. [9] for the same test facility, because the control method was not optimized.

Andrews et al. [10] also demonstrated the importance of the choice of control strategy for a different test facility. The test cell

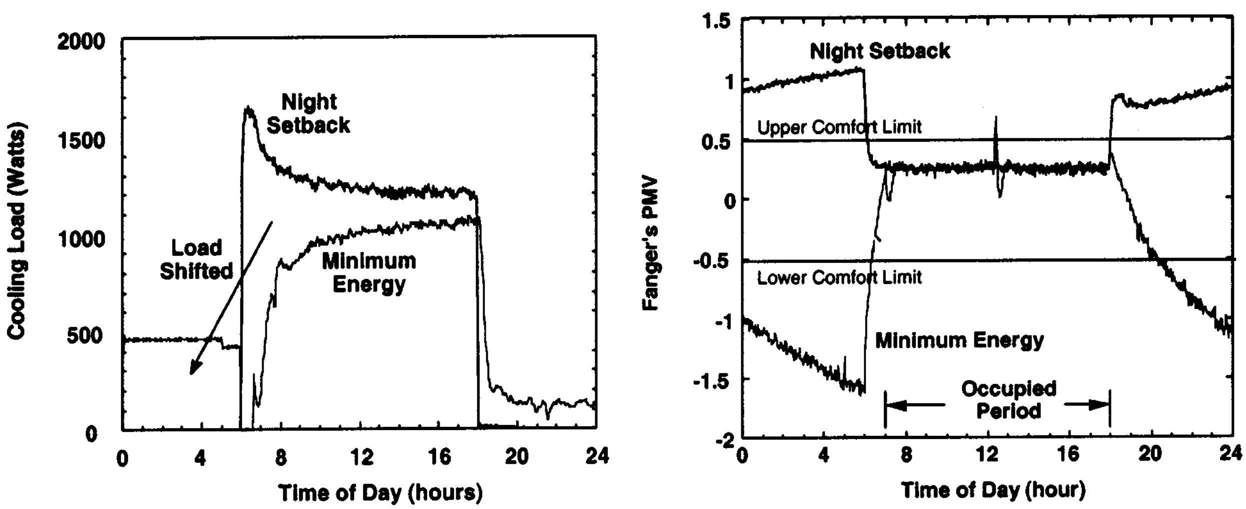


Fig. 4 Measured cooling requirements and PMV for minimum energy and night setback control (from Morris et al. [9])

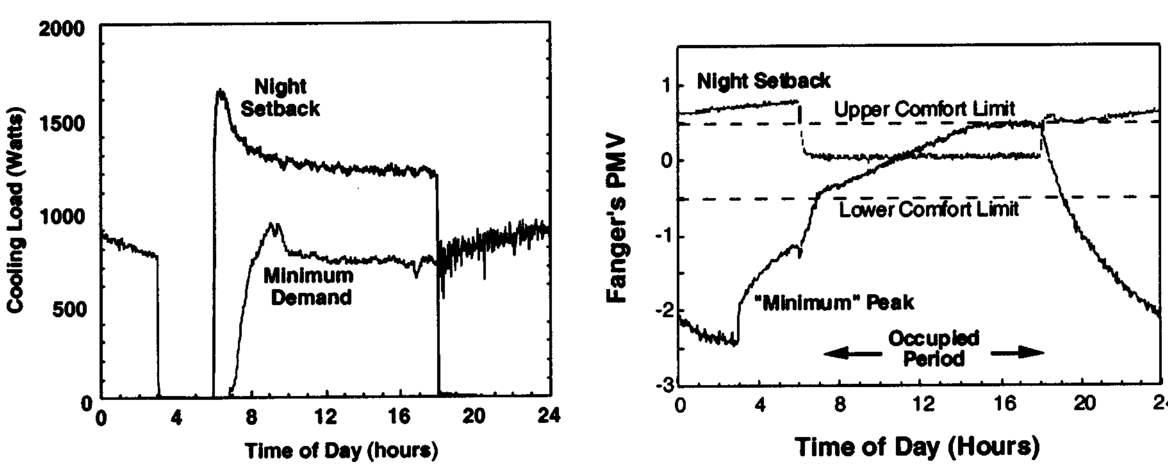


Fig. 5 Measured cooling requirements and PMV for minimum demand and night setback control (from Morris et al. [9])

was constructed with insulated walls, contained concrete blocks, and was housed within a larger building to minimize envelope heat gains. Cooling loads were internally generated. Two different control strategies were considered. Both strategies utilized constant temperature precooling at 72°F during off-peak periods, but differed in the set point adjustments during the occupied period. However, only one of the two discharge strategies resulted in peak load reductions in the afternoon.

The results of Conniff [8], Morris et al. [9], and Andrews et al. [10] were performed in zones having minimal coupling to the ambient. However, ambient coupling reduces the storage efficiency associated with precooling and impacts the cost savings.

Braun et al. [11] considered both internal and external zones and performed tests at the Iowa Energy Center in order to demonstrate the load shifting potential in small commercial buildings. This facility is used for performing research on building controls and has four sets of identical zones (two zones facing east, west, and south with external boundary conditions and two internal zones) on two separate air distribution systems. A third air handling unit serves the remainder of the building, including the office spaces adjacent to the test zones. The original intent of the tests was to run one test air handling unit and the four zones it serves under one control strategy (e.g., night setup) and the second air handling unit and set of zones under a different strategy (e.g., precooling). However, through simulations it was discovered that thermal coupling between the test zones and adjacent zones was significant and there would be significant energy transfers between zones that utilize different zone temperature control strategies. As a result, the entire facility was controlled with a uniform control strategy and two sets of tests over two different time periods were performed. The combination of the four sets of zones is somewhat representative of a small commercial building and not a particularly good candidate for use of building thermal mass. It is a single-story structure with a high exterior surface area to volume ratio and significant thermal coupling with the ground and ambient and to adjacent zones within the building. Furthermore, the test zones have no internal furnishings and the floor is carpeted.

In the first phase of testing, night setup control was employed with a setpoint of 74°F and 90°F during the occupied (7 a.m.–6 p.m.) and unoccupied (6 p.m.–7 a.m.) period. For the second test, the entire building was run with a simple precooling strategy having a daytime cooling setpoint of 74°F from 6 a.m.–6 p.m., a setup setpoint of 90°F from 6 p.m.–12 midnight, and a nighttime precooling temperature setpoint of 68°F from 12 midnight–6 a.m.. Two-day sequences from each test period were found to have very similar ambient and solar variations and were used as the basis for comparing cooling requirements for the two strategies.

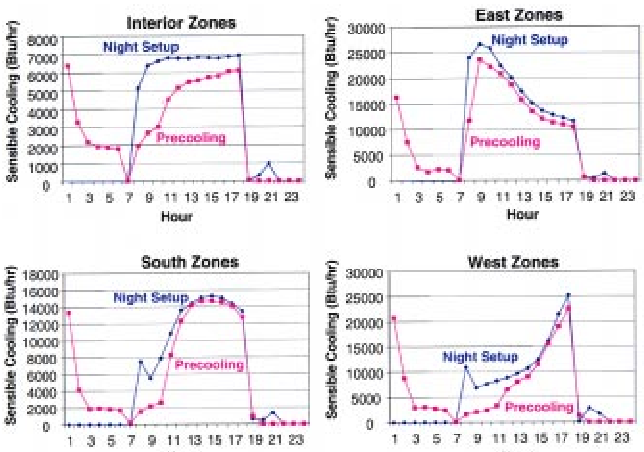


Fig. 6 Comparison of zone sensible cooling loads for interior, east, south and west zones for Iowa Energy Center tests (from Braun et al. [11])

Figure 6 gives individual sensible cooling loads for the test zones on the second day of the two-day sequences for the night setup and precooling tests. There are dramatic differences between the load shapes and strategy comparisons for the different zones. The exterior zones are strongly influenced by solar gains through windows and peak loads are approximately coincident with peak solar gains. On a percentage basis, the largest load shifting associated with precooling occurred for the interior and east zones because of larger cooling requirements during the early hours of occupancy. For the south and west facing zones, there is significant load shifting but relatively small effect of precooling on the peak cooling requirements. For the two-day sequences, the reduction in occupied period cooling load were about 31%, 21%, 18%, and 27% for the interior, east, south, and west zones, respectively. The peak load reductions for the occupied period were about 12%, 15%, 4%, and 3% for the interior, east, south, and west zones, respectively.

Figures 7 and 8 give total sensible cooling loads and average temperatures for all of the test rooms for night setup and precooling test sequences. For night setup control, the loads were relatively flat during the occupied period with a peak load near the end of the day. For the simple precooling strategy, the loads were very small during the early part of occupancy and increased continuously during throughout the day. The occupied period zone temperatures (and comfort levels) were nearly identical for the two strategies. The occupied period load was about 23% less for the precooling tests. The peak load was reduced by about 9%. However, the control strategy was not designed to maximize peak load reduction. Much greater peak load reductions would be possible if the zone temperatures were varied within the comfort region rather than being held constant. Such a strategy would keep

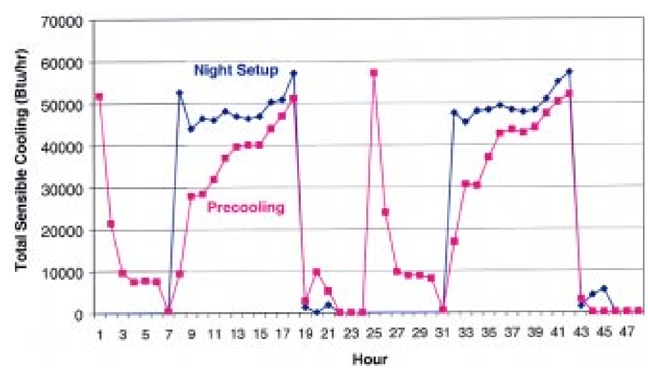


Fig. 7 Comparison of total sensible cooling loads for Iowa Energy Center tests (from Braun et al. [11])

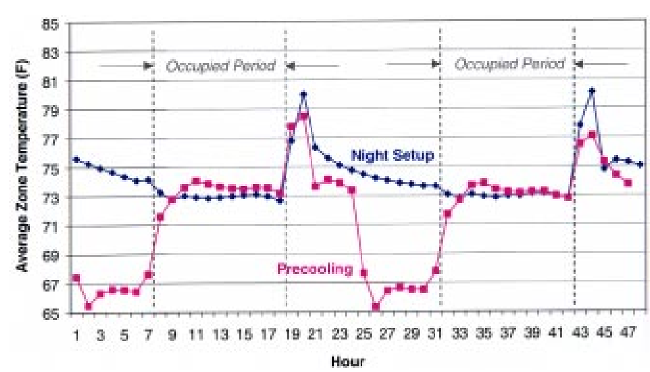


Fig. 8 Comparison of average zone temperatures for Iowa Energy Center tests (from Braun et al. [11])

the zone temperatures low at the beginning of occupancy and raise them later in the day. This would have the effect of increasing the early occupancy loads and decreasing the late occupancy loads.

Field Studies

Both simulation studies and laboratory tests demonstrated significant savings potential for control of building thermal mass. However, they also showed that the cost savings are very sensitive to the application, operating conditions, and method of control. This makes it very difficult to determine appropriate control strategies for a particular field application. Furthermore, it is difficult to document the savings associated with any control strategy in the field, since the operating conditions that influence cooling requirements are not reproducible. One approach for dealing with this problem is to find two nearly identical building zones (i.e., similar occupancy and ambient coupling) and then compare the cooling requirements associated with implementing conventional and precooling strategies. A more accurate method is to use measurements to learn a model for the building energy requirements and then use the model to evaluate the costs associated with different control strategies for identical inputs (e.g., weather, etc.). Both of these approaches have been applied for evaluating building thermal mass control methods.

Ruud, Mitchell, and Klein [12] evaluated the effect of precooling on the on-peak cooling requirements for an existing building. The experiments involved precooling three adjacent stories of the building. The center floor acted as the test floor and the two boundary floors acted to reduce interactions with the rest of the building. Another floor of the building that was not precooled provided the baseline. The results showed only a 10% reduction in the cooling energy required during the occupied period with a substantial increase in the total cooling required and no reduction in the peak cooling requirement. Part of the explanation for this poor performance could be that there was significant convective coupling between zones making it difficult to perform controlled tests. In addition, the building may not have been a good candidate for effective utilization of building thermal storage. The building construction was such that there was a relatively small amount of thermal mass, a weak heat transfer coupling between the thermal mass and the internal air space, and a strong heat transfer coupling to the external ambient conditions. Furthermore, the control was not optimized for this application. However, optimal control for this application may well have been conventional night setup control.

Keeney and Braun [13] used system simulation to develop a control strategy that was then implemented and tested in a large (1.1 million sq. ft.) commercial building located northwest of Chicago. The goal of the control strategy was to utilize building thermal mass to limit the peak cooling load for continued building operation in the event of the loss of one of the four central chiller units. The algorithm was tested using two nearly identical, four-story buildings that are separated by a large separately cooled entrance area. The east building utilized the existing building control strategy while the west building used the precooling strategy developed for this project. Consistent with simulation predictions, the precooling control strategy successfully limited the peak load to 75% of the cooling capacity for the west building, while the east building operated at 100% of capacity.

The emergency control strategy implemented by Keeney and Braun [13] involved precooling at constant zone temperature set points (T_{pre}) of 68°F during the unoccupied period until 5:30 a.m. This was followed by a 30-min warm-up period, where the zone set points were set up to 76°F, so that the cooling system turned off without calling for heating. During this time, the zone air warmed due to lighting and equipment loads. At 6 a.m., the occupied period set points (T_{occ}) were set near the low end of the comfort region at 71°F so that the building *cool* storage was held as long as cooling capacity was available. These set points were maintained until the limit on cooling capacity was reached. After this point, the temperatures in the zones *floated* upwards and discharge of the *cooling* stored in the building thermal mass was accelerated.

Figure 9 shows total chiller load for the east and west buildings for a week of testing within the middle of summer. The cooling coil load profile on Monday is the most dramatic example of the load shifting during this test period. The peak cooling load for this facility often occurs on Monday morning. The cooling limit was achieved on Monday during a period in which a heat emergency

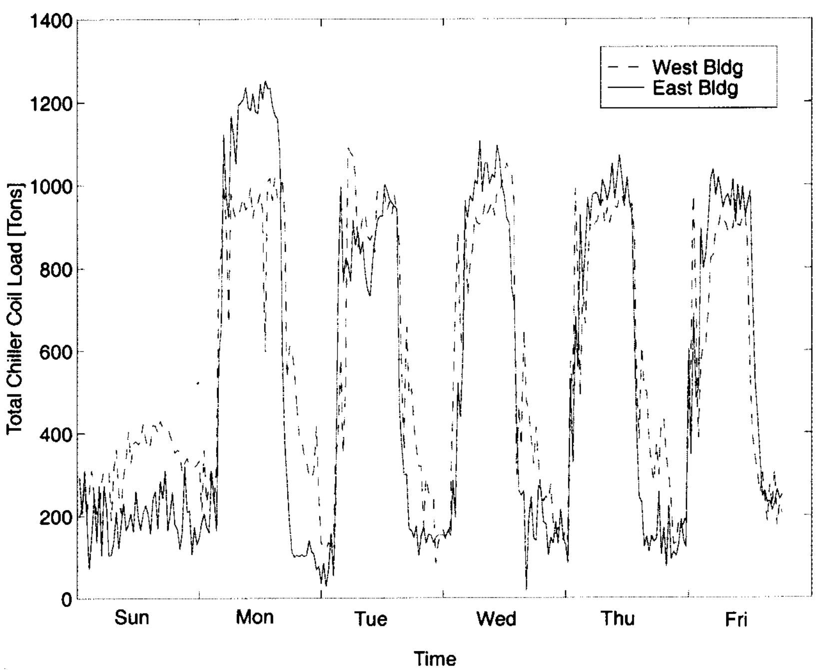


Fig. 9 Total coil load for east and west chiller units (from Keeney and Braun [13])

had been declared in the city of Chicago. The severe ambient conditions were compounded by a power outage that caused a loss of the west side chiller units for approximately 20 minutes. Under these demanding conditions, the precooling strategy maintained occupant comfort while successfully limiting cooling demand of the west side of the building to less than 75% of that for the east side.

The east side cooling requirement was at or below the 75% chiller capacity target for Tuesday through Friday so the emergency precooling strategy was not necessary. For these off-design days, the emergency strategy is not effective in reducing the on-peak cooling requirements because the thermal mass is not fully discharged when the capacity is below the target. However, peak load reduction would occur on off-design days if the target value were reset to a lower value.

Occupant comfort conditions were also monitored during the tests for a representative zone. Figure 10 shows the predicted mean vote (PMV) index plotted as a function of time for Wednesday of the test period under the precooling strategy. At night, the zone conditions were below the ASHRAE limit for occupant comfort. Just prior to occupancy, the warm-up period was initiated which quickly returned the zone conditions to the comfort region. For the remainder of the occupied period, the zone was maintained at cool conditions and the thermal mass was not fully discharged. During the test day depicted in Fig. 10, the limit on cooling capacity was not reached and the comfort conditions remained at a relatively constant level through the day. If the entire comfort range were utilized, additional on-peak load reduction would have occurred.

Braun, Montgomery, and Chaturvedi [14] used data from the same facility used by Keeney and Braun [13] to construct an inverse model and then used the model to estimate savings associated with different zone temperature adjustment strategies. The model utilizes a simplified state-space representation for the building cooling requirements and polynomial curve-fits for the equipment power requirements trained with hourly data in order to provide estimates of hourly power consumption in terms of ambient conditions and zone temperature setpoints. Monthly energy and demand costs determined with the model were within about 5% of a summer utility bill.

The inverse model was run for a three-month period (June to August) to estimate the savings potential of different control strategies for the field site. Table 1 shows energy, demand and total costs for cooling and total savings relative to Night Setup. Figure 11 shows the setpoint variations associated with the different control strategies. For Night Setup, the setpoint was 73°F (22.8°C) during occupancy (7 a.m.–5 p.m.) and set to 80°F at other times. The Light Precool and Moderate Precool strategies precooled the building at a fixed setpoint of 67°F (19.4°C) prior to occupancy and maintained a fixed setpoint of 73°F (22.8°C) during occupancy. The Light Precool began at 3 a.m., whereas the Moderate Precool started at 1 a.m. The Extended Precool was identical to the Moderate Precool, except the setpoint at occupancy was changed to 69°F (20.6°C) until the on-peak period began at 10 a.m., when it was raised to 73°F (22.8°C). The Maximum Discharge strategy was the same as the Extended Precool, except the setpoint for the on-peak, occupied period was 77°F (25°C). The *Slow* Linear Rise strategy was a modification of the Maximum Discharge strategy, where the setpoint was raised linearly over the entire on-peak, occupied period (9 hr in this case) between 69°F (20.6°C) and 77°F (25°C).

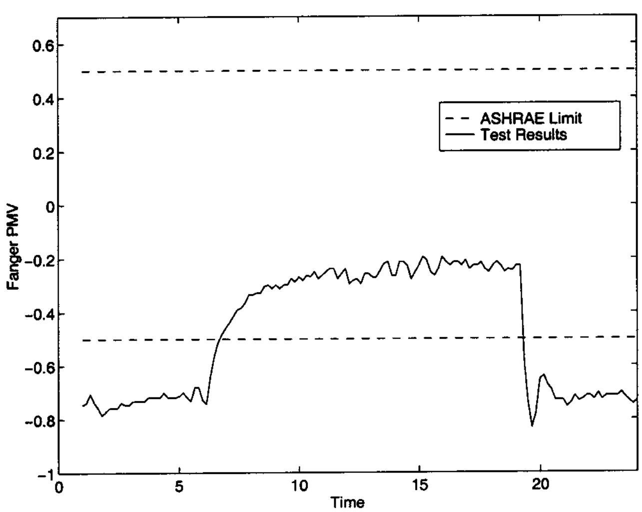


Fig. 10 Measured comfort index under precooling strategy (from Keeney and Braun [13])

Table 1 Cooling season energy, demand and total costs and savings potential of different control strategies for Chicago field site (from Braun et al. [14])

Strategy	Energy costs ($)	Demand costs ($)	Total costs ($)	Savings (%)
Night Setup	90,802	189,034	279,836	0.0
Light Precool	84,346	147,581	231,928	17.1
Moderate Precool	83,541	143,859	227,400	18.7
Extended Precool	81,715	134,551	216,266	22.7
Maximum Discharge	72,638	91,282	163,920	41.4
Slow Linear Rise	77,095	141,124	218,219	22.0

The strategies that did not utilize the entire comfort range during the occupied period (Light Precool, Moderate Precool and Extended Precool) all provided about 20% savings relative to Night Setup. Each of these strategies reduced both energy and demand costs. However, the demand costs and demand cost reductions were significantly greater than the energy costs and savings. The decreases in energy costs were due to favorable on-to-off peak energy rate ratios of about 2 to 1. High on-peak demand charges of about $16/kW provided even greater incentives for use of precooling. The savings increased with the length of the precooling period, particularly when the precooling was performed close to the onset of on-peak rates. The Maximum Discharge strategy, which maximizes discharge of the thermal storage within the structure, provided the largest savings (41%). Much of the additional savings were due to reductions in the demand costs. The Linear Rise strategy was no better than the Extended Precool with slightly better energy savings and worse demand savings.

Typical rate structures were obtained for five locations (Boston, Chicago, Miami, Phoenix, and Seattle) and used to carry out simulation studies to analyze the overall impact of location on the savings potential for use of building thermal mass. Figure 12 gives air conditioning utility cost savings estimates associated with each strategy and location determined using the utility information shown in Table 2. Savings were achieved in all locations except for Seattle. The greatest savings (50%) were associated with the Maximum Discharge strategy implemented in Boston. Similar savings were achieved in Chicago and Miami, with some lower savings in Phoenix. The negative savings in Seattle means that Night Setup is the best strategy for this location. A greater penalty is associated with greater precooling in Seattle. However, night ventilation was not considered in this study. The use of night ventilation could result in some savings for precooling Seattle.

State-of-the-Art and Beyond

Significant savings potential for use of building thermal mass has been demonstrated in commercial buildings using simulation, controlled laboratory testing, and field demonstrations. However, the savings are sensitive to many factors, including utility rates, type of equipment, occupancy schedule, building construction, climate conditions, and control strategy. The most important factor for savings is probably the utility rate structure. In the absence of time-of-use and demand charges, positive savings depend upon having conditions that allow for night ventilation precooling or equipment with very favorable part-load performance. However, very significant savings are possible for most modern commercial buildings that have favorable off-peak utility rates regardless of equipment type, building construction, and climate. There are some exceptions: constant-air-volume (CAV) systems with reheat and buildings with 24-hr occupancy are not good candidates for application of building thermal mass control strategies. There is also a greater opportunity for savings in large commercial buildings than smaller ones because of a smaller ratio of external area to thermal mass, the use of heavier weight materials, and the availability of more favorable electrical rate structures. However, it may be easier to develop an intelligent controller for small commercial buildings because they typically use packaged air conditioners with a single thermostat controlling a single unit for individual zones. In large commercial buildings, the equipment tends to centralized and serves many zones. The systems tend to be complex and one of a kind with specialized control software.

There are several technical obstacles to widespread implementation of building thermal mass control in large commercial buildings. First of all, it is necessary to have digital thermostats that are networked to a centralized control system. Secondly, the control system should be easily configured so as to allow communication of a global setpoint to all of the thermostats. These two features are not very common in existing installations. Thirdly, it is necessary to develop a site-specific control methodology for a given building. This is not an easy task. However, the savings potential is significant enough to warrant additional costs associated with new control hardware and software.

Very little work has been done in developing general control approaches for use of building thermal mass. The ultimate solution would be to employ an optimal controller that determines a trajectory of zone temperature setpoints by minimizing an integral cost function evaluated using models for transient cooling requirements and air conditioning equipment performance, utility rate information, and weather forecasts. The controller could learn the models using site-specific measurements. The models and optimization approaches would need to be relatively simple with a small number of measured inputs in order to allow low-cost implementation. Significant research is necessary before an optimal controller is practical. For large commercial buildings, it is much more likely that fixed control strategies will be implemented in the near term.

A fixed control strategy should prescribe how zone temperature

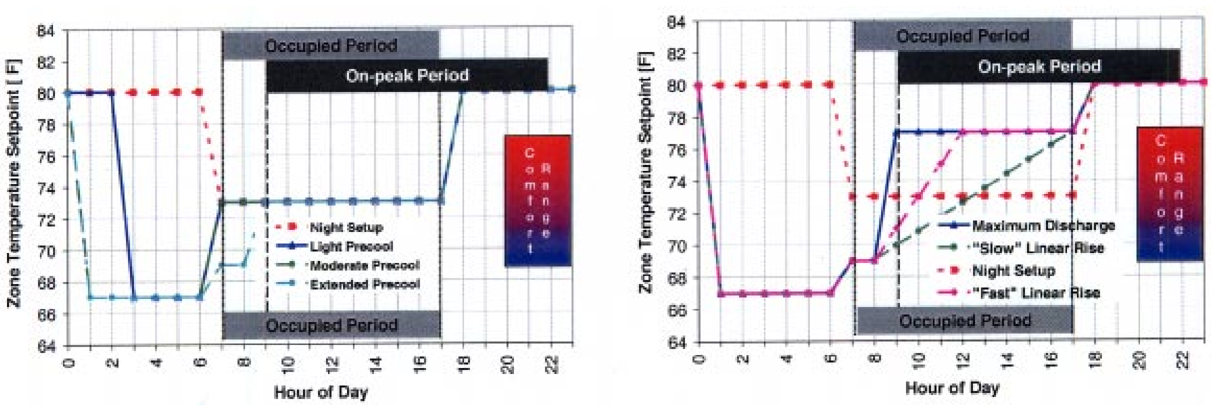


Fig. 11 Weekday hourly zone temperature setpoint definitions for *a*) *Night Setup*, *Light Precool*, *Moderate*, and *Extended Precool* strategies and *b*) *Night Setup*, *Maximum Discharge*, and *Linear Temperature Rise* strategies (from Braun et al. [14]).

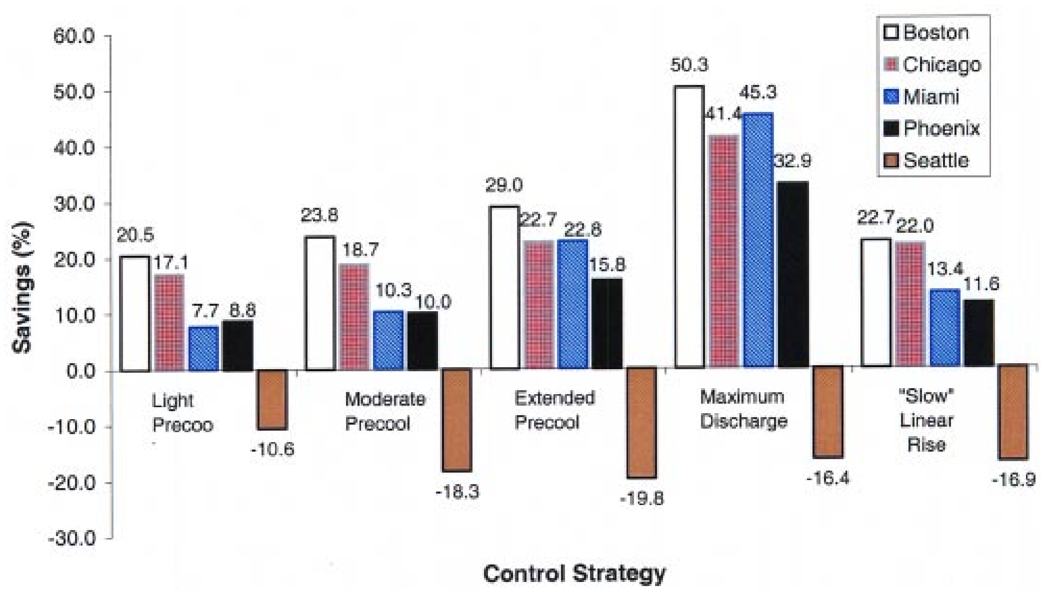


Fig. 12 Regional comparison of the savings potential of different control strategies under different climatic conditions and different utility rate structures (from Braun et al. [14])

Table 2 Utility rate structures for different locations

City	Energy (c/kWh) Off-Peak	On-Peak	Energy Cost Ratio	Demand ($/kW) On-Peak	Peak Hours
Boston	0.6	2.9	4.7	18.87	9 a.m.–10 p.m.
Chicago	2.3	5.2	2.3	16.41	9 a.m.–10 p.m.
Miami	1.1	2.8	2.5	6.25	12 a.m.–9.p.m.
Phoenix	2.7	5.1	1.9	14.82	11 a.m.–9 p.m.
Seattle	3.2	3.2	1.0	1.46	6 a.m.–10 p.m.

set points vary over time. However, different strategies are appropriate for minimizing energy and demand costs. For energy cost minimization, the zone temperature set points should be raised to the upper comfort limit as quickly as possible after the onset of on-peak utility rates. For demand cost minimization, the set points could be kept at the lower limit of comfort with an appropriate limit on the peak power consumption. When the actual power reaches the limit, then the zone temperatures would float. The limit should be the lowest value that would just keep the zone temperature within the comfort region. This limit would need to change according to the expected cooling requirements. Estimating the appropriate demand limit is a difficult, yet important problem. Determining the appropriate time to transition between energy cost and demand-limiting strategies is also difficult. Since demand-limiting strategies have a greater influence on comfort than energy cost strategies, it is probably best that a human operator turn them on manually each day.

For large commercial buildings, site-specific control strategies could be identified using a detailed description of the building and equipment and utility rates along with a system simulation tool. The disadvantages of this approach are that it requires a lot of initial effort and the strategies cannot adapt to changes that may occur over time (e.g., occupancy, utility rates). Another somewhat similar approach would be to use short-term data to train models that could be used to identify control strategies. For instance, Braun et al. [14] and Chaturvedi et al. [15] presented inverse models that might be used with this approach. The trained models could be used to develop/update site-specific control strategies. Ultimately, similar inverse models could be used within an on-line optimal controller.

It may also be possible to develop guidelines for application of and expected savings from building thermal mass control strategies that can be used by controls engineers to facilitate implementation within control systems in large commercial systems. The guidelines could be developed through use of simulations for a range of different building types, equipment, climates, and utility rates. For small commercial buildings, it may be practical in the near term to develop a simple optimal controller and embed it within a smart thermostat. Existing thermostats in small commercial buildings provide direct on/off control of packaged cooling equipment (as opposed to the cascaded controls used in central chiller plants) and could be readily replaced with smart thermostats at relatively low cost. The dynamics of the calls for cooling could be learned through adaptation of a simple dynamic model. Utility rates and general equipment characteristics could be entered as parameters during configuration of the controller.

Although the paths to commercialization are not known, it is apparent that the benefits associated with control of building thermal mass are such that commercial products will be developed and begin to penetrate the marketplace within the next decade.

References

[1] Braun, J. E., 1990, ‘‘Reducing Energy Costs and Peak Electrical Demand Through Optimal Control of Building Thermal Storage,’’ ASHRAE Trans., **96**(2), pp. 876–888.

[2] Snyder, M. E., and Newell, T. A., 1990, ‘‘Cooling Cost Minimization Using Building Mass for Thermal Storage,’’ ASHRAE Trans., **96**(2), pp. 830–838.

[3] Keeney, K. R., and Braun, J. E., 1996, ‘‘A Simplified Method for Determining Optimal Cooling Control Strategies for Thermal Storage in Building Mass,’’ International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research, **2**(1), pp. 1–20.

[4] Chen, T. Y., 2001, ‘‘Real-Time Predictive Supervisory Operation of Building Thermal Systems With Thermal Mass,’’ Energy Build., **33**, pp. 141–150.

[5] Nagai, T., 2002, ‘‘Optimization Method for Minimizing Annual Energy, Peak Energy Demand, and Annual Energy Cost Through Use of Building Thermal Storage,’’ ASHRAE Trans., **108**(1).

[6] Rabl, A., and Norford, L. K., 1991, ‘‘Peak Load Reduction by Preconditioning Buildings at Night,’’ Int. J. Energy Res., **15**, pp. 781–798.

[7] Andresen, I., and Brandemuehl, M. J., 1992, ‘‘Heat Storage in Building Thermal Mass: A Parametric Study,’’ ASHRAE Trans., **98**(1).

[8] Coniff, J. P., 1991, ‘‘Strategies for Reducing Peak Air Conditioning Loads by Using Heat Storage in the Building Structure,’’ ASHRAE Trans., **97**, pp. 704–709.

[9] Morris, F. B., Braun, J. E., and Treado, S. J., 1994, ‘‘Experimental and Simulated Performance of Optimal Control of Building Thermal Storage,’’ ASHRAE Trans., **100**(1), pp. 402–414.

[10] Andrews, J. W., Piraino, M., and Strasser, J., 1993, ‘‘Laboratory Testing of Control Strategies to Reduce Peak Air-Conditioning Loads,’’ ASHRAE Trans., **98**(1), pp. 910–918.

[11] Braun, J. E., Lawrence, T. M., Klaassen, C. J., and House, J. M., 2002, ‘‘Demonstration of Load Shifting and Peak Load Reduction With Control of Building Thermal Mass,’’ Proc. of 2002 ACEEE Conf. on Energy Efficiency in Buildings, Monterey, CA.

[12] Ruud, M. D., Mitchell, J. W., and Klein, S. A., 1990, ‘‘Use of Building Thermal Mass to Offset Cooling Loads,’’ ASHRAE Trans., **96**(2), pp. 820–829.

[13] Keeney, K. R., and Braun, J. E., 1997, ‘‘Application of Building Precooling to Reduce Peak Cooling Requirements,’’ ASHRAE Trans., **103**(1), pp. 463–469.

[14] Braun, J. E., Montgomery, K. W., and Chaturvedi, N., 2001, ‘‘Evaluating the Performance of Building Thermal Mass Control Strategies,’’ International Journal of Heating, Ventilating, Air-Conditioning and Refrigeration Research, **7**(4), pp. 403–428.

[15] Chaturvedi, N., and Braun, J. E., 2002, ‘‘An Inverse Gray-Box Model for Transient Building Load Prediction,’’ International Journal of Heating, Ventilating, Air-Conditioning and Refrigeration Research, **8**(1), pp. 73–100.